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9914567.4

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1. Your reference

    P14919

2. Patent application number
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3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

    THAMES WATER UTILITIES LIMITED
    GAINSBOROUGH HOUSE,
    MANOR FARM ROAD,
    READING, BERKS RG2 0JN.

    Patents ADP number *(if you know it)*

    If the applicant is a corporate body, give the country/state of its incorporation

    UNITED KINGDOM 04125600003

4. Title of the invention

    CORRELATION ANALYSIS IN THE PHASE DOMAIN

5. Name of your agent *(if you have one)*

    "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

    EDWARD EVANS & CO
    CHANCERY HOUSE
    53-64 CHANCERY LANE
    LONDON WC2A 1SD

    Patents ADP number *(if you know it)*

    661001

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Number of earlier application	Date of filing *(day / month / year)*

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    a) any applicant named in part 3 is not an inventor
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Description	8
Claim*(s)*	
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Request for preliminary examination and search *(Patents Form 9/77)*	
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CORRELATION ANALYSIS IN THE PHASE DOMAIN.

This invention relates to the detection of a common signal within two (or more) input signals using correlation based techniques, and is more specifically, although not exclusively, concerned with the detection and location of leaks in water mains using correlation based techniques.

There are many applications in which signals are analysed using the technique of crosscorrelation of two data streams. This technique is specifically useful when analysing or comparing two or more composite time sequential signals within which it is believed that there is a common signal.

One area in which crosscorrelation is used is in the analysis of water leak sounds conducted along water mains, specifically locating leaks on water mains using audio sensors. The technique involves the detection and location of a common leak sound in the signals from two listening devices. It is anticipated that the sound of a leak heard remotely at one location will contain significant similarities to the sound of the same leak heard remotely at a second location. The two audio signals are therefore likely to exhibit a peak in their crosscorrelation function if there is a common source present, the position of the peak giving the time delay when the signals are similar. The peaks in the crosscorrelation function can therefore be used to deduce the location of common audio signals via the velocity of the sound in the pipe and the physical surroundings of the noise source. If the nature and persistency of the sound is indicative of leaks then there is a high probability that a leak has been found and located.

The analysis techniques described herein both for the prior art methods and the present invention are also applicable in many other technical areas. These include the following: the analysis of odd mechanical noise in equipment; the assessment of quality of objects by the noise that they make while travelling along a production line;

the assessment of the performance of wheeled vehicles on road or railway tracks; the analysis of road or rail surfaces by the analysis of the sound of the passage of vehicles either on a mobile platform or at a fixed location; and the measurement of closely similar recordings (the analysis of their true relationship from a high quality digital copy to a different performance of the same song that sounds very similar).

Correlation processing techniques are frequently performed using the following process: calculate the Fourier transform of the data sets representing the two waveforms to be correlated, thereby transforming the data into the frequency domain; performing the required multiplications; and calculating the inverse Fourier transform to display the correlation function in the time domain. Often the Fast Fourier Transform is used since this allows a considerable reduction in the processing required to generate the correlation function. These techniques are well known and generally used.

The general correlation processing techniques work well, and several devices are available to perform this task. However, when the signal to noise ratio is poor and/or the bandwidth of the signals is restricted due to the propagation of the signal then the crosscorrelation function inevitably becomes degraded, with the peaks becoming less distinct or even hidden by the noise. Thus filters are used to obtain the optimum signal to noise ratio and correlation accuracy.

Noise which may be present in a signal can be considered as two distinct forms: random noise and clutter. Random noise is unpredictable on a short timescale, but has a zero mean. It may be removed by averaging over a sufficiently long period. Clutter is a function of the detected signal such as, for example, echoes and resonance, which cannot be removed by averaging.

The signal to noise ratio may be improved by filtering the input signals to reduce the bandwidth. However, as the bandwidth is reduced the width of the correlation peak tends to increase. This makes it difficult to determine the time delay when the signals

are similar, and thereby makes it more difficult to determine the location of the common signal. It is therefore important to filter the signal to exclude only those bands which do not contain the useful signal. However, the prior art methods of selecting the bands are imprecise.

For example, in the case of water leak detection the audio noise signal picked up from the pipe will be a combination of the leak noise and other external or waterborne sounds. In order to improve the signal to noise ratio of the input signals the operator of a water leak detector may analyse the spectrum of the input signals to determine where signal power is significant. Filters are then set to remove the frequencies in which the signal power is not significant. This method usually provide some improvements, but does not guarantee a band with good correlation. The operator will generally need to use a combination of experience and trial and error to improve the shape of the correlation function. This process can be time consuming, often taking tens of minutes at each leak site.

The present invention seeks to mitigate these disadvantages, and to provide an improved method of detection and location of a signal using correlation based techniques.

According to a first aspect of the invention, there is provided a method for detecting and locating a common signal within two input signals using correlation based techniques, comprising providing at least one filter by analysing the phase of the input signals in the frequency domain; filtering the input signals in the frequency domain using said at least one filter; and performing crosscorrelation of the input signals, whereby to locate a source of the common signal.

The signals may be audio signals.

According to a second aspect of the invention, there is provided a method for detecting and locating leaks in a fluid carrying pipe such as a water main using correlation based techniques, comprising providing an input signal from each of at least two transducers; using the analysis of the phase of the input signals in the frequency domain to filter the input signals in the frequency domain; and performing crosscorrelation of the input signals, whereby to detect a source of a leak.

The methods may include constructing a filter for suppressing frequencies which do not exhibit a sufficient degree of coherence. The methods may also include constructing a filter for removing frequencies which do not have sufficient amplitude. The methods may further include constructing a filter for suppressing frequencies which do not exhibit steady phase progression over adjacent frequencies. The methods may yet further include constructing a filter for compensating the input signals for dispersion effects.

A specific embodiment according to the invention is provided for the detection of leaks in water mains. The apparatus may comprise a novel correlator which is provided on a standard field engineer's Personal Computer. The novel correlator may include a suite of signal processing algorithms and a suitable Graphical User Interface. Like current correlators the novel correlator would receive its inputs from two transducers.

As explained hereinbefore, the characteristics of a correlated signal are that it has similar features in its waveform (although one may be delayed with respect to each other and the whole buried in noise and interference). The crosscorrelation of two input signals will only produce a significant peak if the frequency bands which make up those input signals have a stable phase relationship with respect to each other, i.e. the input signals have a narrow band coherence. Filtering of the two input signals to remove or suppress the frequencies which do not exhibit a sufficient degree of coherence will therefore enhance the peak in the crosscorrelation function. Frequencies which do not exhibit sufficient coherence need not be included in the

final result because they will only be contributing noise. The filter profile for the signal may therefore be determined automatically.

The novel correlator includes a phase confidence filter, which is constructed to suppress the frequencies in the input signals which do not exhibit a sufficient degree of coherence. The phase confidence filter effectively indicates the estimation of how well a particular frequency will correlate, and is the result of analysing the phase stability between the input signals. One possible method for constructing the phase confidence filter would be first to calculate a phase confidence function using the following steps: to calculate the complex Fourier transform for each of a number of sections of the two input signals; to calculate the average vector sum of the phase difference between the two input signals for each frequency; and then to calculate the magnitude of the vector sum and normalise the result. Thus a function is provided which has a value of 1.0 for a given frequency which shows perfect coherence, and tends to 1 n if the phase differences for a given frequency are random, where n is the number of samples taken. The phase confidence function may then be used as an optimal frequency weighting function to construct a filter which will include only those frequencies which contribute usefully to the crosscorrelation of the input signals.

The phase confidence filter is used in combination with an automatic band filter. The automatic band filter is constructed based purely on the amplitude of the input signals. The filter is designed to select frequencies of large amplitude, which are likely to be prominent in the crosscorrelation, and by reducing the bandwidth to hence improve the signal to noise ratio. This filter may be constructed by simply applying a digital threshold to the product of the spectra of the input signals. The threshold may be configurable by the user. The phase confidence filter and the automatic band filter are applied separately to the data.

The use of the automatic band filter addresses one practical disadvantage of the phase confidence filter. This is that some of the noise in the input signals can have highly

correlated noise as a result of imperfect digitisation, this effect, seen usually at high frequencies, can produce a substantial phase confidence measurement. The automatic band filter suppresses frequencies where the signal to noise ratio is poor and this artifact is most likely to be seen.

The effect of using the phase confidence filter in combination with the automatic band filter is shown in Figs. 1 to 4. Figs. 1 and 2 show a first input signal 1 and a second input signal 2 respectively, both in the frequency domain. The crosscorrelation function 7 for the unfiltered first and second signals is shown in Fig. 3. The phase confidence filter 3 and the automatic band filter 4 are constructed for the first and second signals and applied to the signals in the frequency domain to produce a filtered first signal 5 and a filtered second signal 6. The crosscorrelation function 8 for the filtered first and second signals is shown in Fig. 4. The improvement between the crosscorrelation functions 7 and 8 can clearly be seen. There is improved clarity, with reduced background level and less ambiguous peak location.

If the common features in the input signals contain some degree of time dependency, then the phase relationship will not be stable. The use of the phase confidence filter calculated using the method above may blur the results. An alternative method for calculating the phase confidence filter would be to consider the phases for each individual section of the input signals. The process could then adapt if the phase appeared to be stable to lengthen the average by including further sections to improve the estimate.

This method could also be adapted to track the signals if they were time dependent. Consider, for example, a signal which is very noisy but has a particular value which may be either constant or changing over time. If this value is constant then it is possible to average the signal to produce the value accurately. However, if the value is changing then a compromise must be made between the number of samples over which the signal is averaged, and the rate at which the value is varying.

If to a first approximation this variation is linear it is relatively easy to produce a root mean square best straight line fit that continually updates as the data comes in. If the variation is non-linear then some means must be found of releasing the linear constraint but still producing a good curve fit. If the calculation process also produces two alternative straight line fits, one based on the first half of the data, and the other based on the second half of the data (they could be updated every other data point to ensure an even number of points) if the two lines show coherent deviation above some threshold a track deviation can be initiated. Thereby, an adaptive signal tracking process may be developed.

The novel correlator also includes a filter based on a consideration of the phase relationships between adjacent frequencies of the input signals. The phase differences may exhibit a steady progression of phase over the range of frequencies which are coherent. The source of this result can be visualised by considering a single correlation peak, a peak in the time domain is created by frequencies adding up in phase in the frequency domain. Consider firstly a centre correlation peak (often the result of an instrumental artefact or interfering signal) which is located in the centre of the correlation range and which corresponds to correlation where there is zero relative delay between two input signals. In this case the frequencies have the same or very similar phase, and therefore the phase does not change with frequency. A centre correlation peak may be removed by constructing a filter to remove frequencies having the same phase. Note, however, that exact centre correlation in the leak, although unlikely, is not impossible.

If the correlation peak represents a delay between the input signals then adjacent frequencies are shifted in phase by an amount defined by the phase shift caused by the delay acting on the frequency difference. Frequencies evenly spaced in a Fourier Transform will exhibit a linear change of phase between adjacent correlated phases.

Considering the phases of sequential frequencies can have the advantage when the propagation bandwidth is very narrow resulting in a broad correlation peak because the phase progression can be "unwrapped" and a straight line fitted to it.

The existence of a second major peak in the correlation result will add a second linear progression to the phase pattern. The two phase progressions will add as vectors with the result that as the relative phases of the two linear progressions move in and out of phase the main peak will be advanced and retarded in phase giving a ripple in the phase results.

Alternatively, the case where the velocity of the sound is frequency dependent may be utilised. In this case the phase progression for adjacent frequencies in a single correlation peak will not be linear. This non-linearity may be tracked. This will allow either the compensation of results for dispersion where the correlation is spread by its effects or the identification and measurement of the dispersion effects using known sound sources.

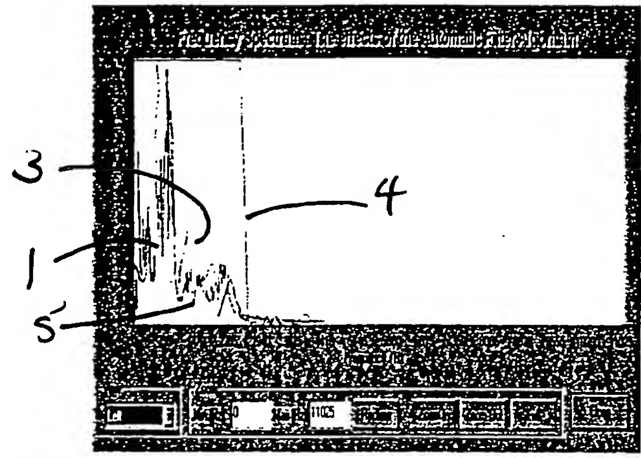

FIG. 1

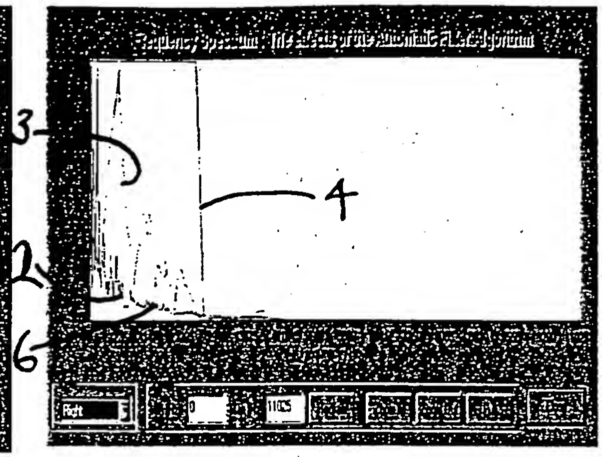

FIG. 2

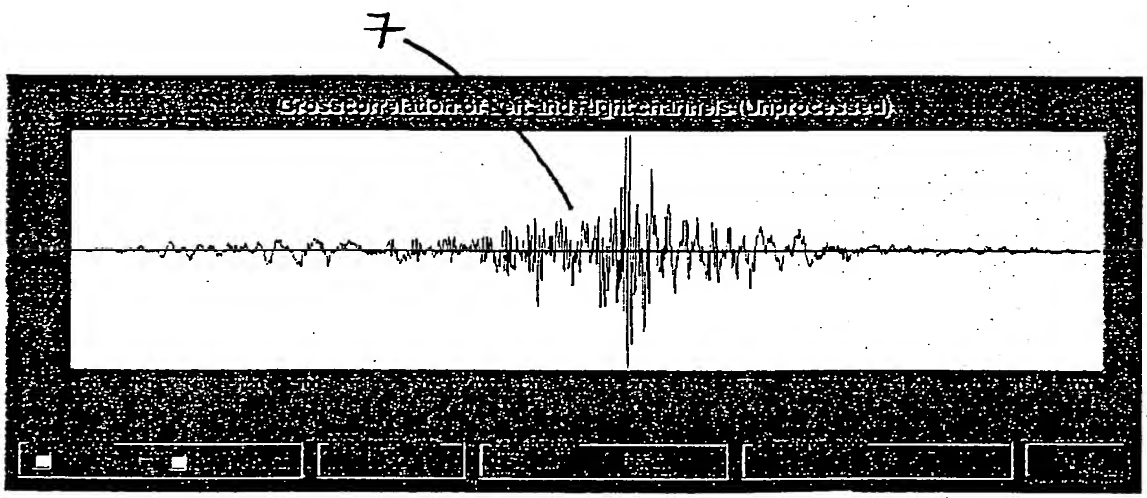

FIG. 3

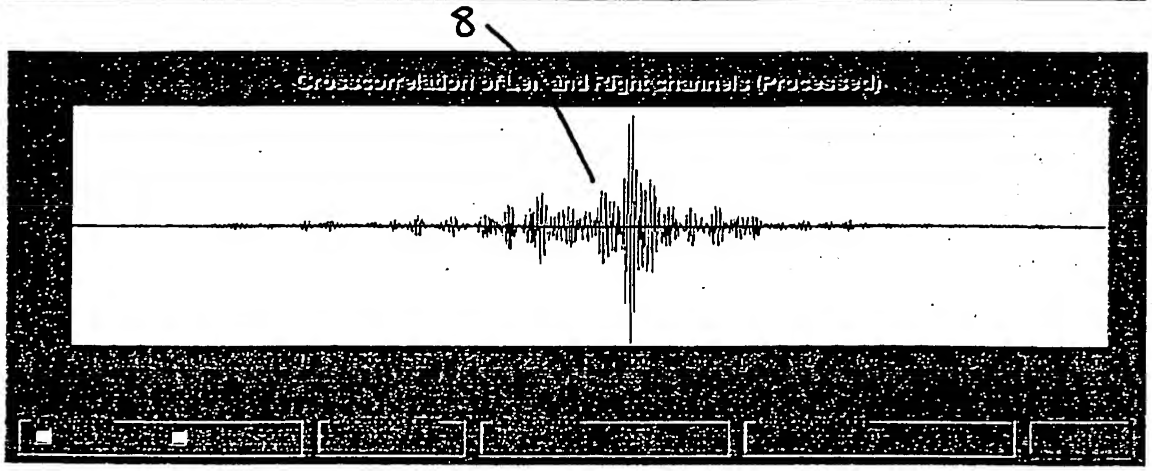

FIG. 4

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